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ORIGINAL PAPER

Interaction analysis between slenderness ratio and resin content on mechanical properties of particleboard

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Abstract: The interaction between particle size and resin content is one of the most important structural parameters that can influence the accuracy of predictions about wood-composite properties. We developed three kinds of equation (linear, quadratic, and exponential) for each mechanical property of particleboard based on slenderness ratio and resin content at a constant density ($0.7 g\cdot cm^{-3}$). Results from SHAZAM software (version 9) suggested that the quadratic function was not significant, but the linear and exponential functions were significant. The interaction between particle size and resin content was analyzed by Maple 9 software. The results indicated that an exponential function can better describe the simultaneous effect of slenderness and resin content than a linear equation. Under constant resin content, particles with higher slenderness ratios increased more in modulus of rupture (MOR) and modulus of elasticity (MOE) than did particles with lower slenderness ratios. Edge withdrawal resistance (SWRe) values did not increase with increasing slenderness ratio.

Keywords: mechanical properties; particle size; slenderness ratio; linear equation; exponential equation

Introduction

Particleboard is primarily used in carpentry, furniture and construction. Annual particleboard production increased rapidly in Iran from 333 000 m^3 in 1998 to 637 000 m^3 in 2008. (Azizi 2008; Aziza et al. 2009). In the particleboard industry, mechanical properties such as bending strength, modulus of elasticity and internal bond strength are the most appropriate parameters for determining board quality (Fernandez et al. 2008). On the other hand, determining the mechanical properties of particleboard according to standard methods is time-consuming and requires sophisticated testing equipment (Semple et al. 2006; Lin and Huang 2004). Predicting mechanical properties using models is easier and cheaper than determining them through standard experimental methods, and also provides valuable information to improve process control and reduce production cost (Cook and Chiu 1993).

Several models are used to predict the mechanical properties of particleboard. Modulus of rupture (MOR) and modulus of elasticity (MOE) are modeled based on slenderness ratio (length of particle / thickness of particle), orientation of wood particle on panel surface, and panel density (Wang and Lam 1999). Bending properties of oriented strand board (OSB) panels were investigated as a function of shape, size, and distribution of wood strand (Takuya et al. 2004). They showed the undesirable disorientation of strands decreased bending strength. Barnes (2001) reported a model to investigate the effect of strand length and thickness on the strength of oriented wood composites. He showed that grain angle in the strands affected parallel strength properties of OSB panels. The content, type, and location of resin within the panel are the most important factors influencing the strength of wood composite (Maloney 1970). Dai et al. (2008) showed that internal bond strength (IB) was increased by increase in product density, resin content, and particle thickness. Cook and Chiu (1993) designed a radial basis function (RBF) based on processing parameters for predicting the IB strength of particleboards. They found the model could predict IB strength with 12.5% error, and they attributed this value of error to the size and geometry of particles, as these factors were not considered in their model. Edge screw withdrawal resistance (SWRe) is one of the most important mechanical properties of particleboard for determining its bond quality. SWRe has been modeled based on density, IB, and screw conditions (Eckelman 1973; Fujimoto and Mori 1983; Semple 2006). The influence of particle geometry on SWRe has only rarely been investigated (Post 1961; Sackey et al. 2008).

Particle surface area partially determines the percent resin coverage on particle surfaces (Hebin et al. 1994; Yuebin et al.

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1996; Sun and Arima 1999). The diameters of resin droplets and the distance between droplets determine the proportion of surface covered by resin (Groves 1998). Many studies showed that particles with large surface area had larger areas available for resin coverage and this probably accounted for the higher recorded board strength (Maloney 1977; Sun and Armia 1999; Miyamoto et al. 2002; Scott 2001; Lin et al. 2004). Although the relationship of particle size to resin content is a key parameter determining the strength of particleboard, this subject received little attention in previous studies.

Our research objective was to test whether differences in slenderness ratio and resin coverage can be used to increase the accuracy of a predictive model of particleboard strength. The objective of this study was to investigate which function (linear, quadratic, or exponential) best describes the interaction between slenderness ratio and resin content, and predicts mechanical strength with least error.

Materials and methods

Small-diameter logs of poplar (*Populous alba*) were cut into blocks of 50 mm×50 mm×10 mm and then ground with a laboratory hammer mill. Particles were dried to a moisture content of less than 3%. After drying, the particles were sifted through three hand-held screens with 5, 8, and 12 mesh (Fig.1). The length, width, and thickness of 5 g screened particles for each particle size (+5; −5 +8; -8 +12; −12) were measured with a micrometer caliper. Average dimensions of classified particles are shown in Table 1. Urea formaldehyde (55% solid content) was then sprayed on the particles as an adhesive and mats were formed and pressed with 35 kg·cm^{-2} pressure at 180°C for 5 min. Finally, 108 single-layer particleboards with three levels of density (0.65, 0.7 and 0.75 g·cm^{-3}), three levels of percentage of adhesive (8, 9.5, and 11%) and four levels of particle size (+5; −5 +8; −8 +12; −12) were manufactured in the laboratory. Then the boards were kept at (65±5)% relative humidity at (20±2)°C for two weeks for moisture conditioning. The modulus of rupture, modulus of elasticity, and internal bond strength were quantified for samples cut according to EN 310, EN 319, and EN 320 standards, respectively, and then samples were tested by INSTRON 4489 mashine.

Table 1. The features of particles for each mesh

Mesh	Length (mm)	Width (mm)	Thickness (mm)	L/W	L/T	W/T
A (+5)	55.1 (7.7) *	7.9 (3.5)	1.19 (0.3)	6.97	46.3	5.85
B (-5 +8)	28.4 (3.1)	4.7 (1.3)	0.84 (0.1)	6.05	33.7	5.57
C (-8 +12)	13.98 (3.8)	2.18 (0.4)	0.65 (0.2)	6.41	21.51	3.35
D (+12)	3.98 (2.3)	0.82 (0.2)	0.31 (0.1)	4.85	12.84	2.65

* The value in the parenthesis represents standard deviation.

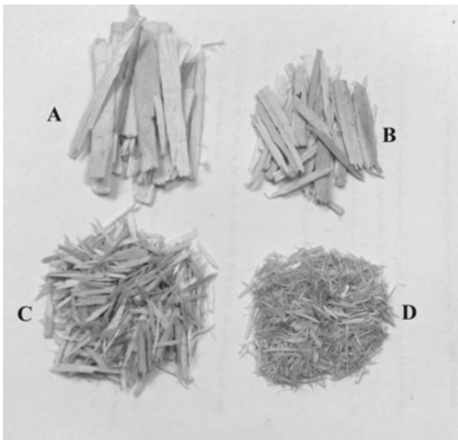

Fig. 1 Four types of particles. A: +5 mesh; B: -5 + 8 mesh; C: -8 +12 mesh; D: -12 mesh.

Results and discussion

Three types of functions (linear, quadratic and exponential) were obtained using SHAZAM software (version 9). The quadratic function was not significant so the linear and exponential functions were considered for predicting MOE, MOR, IB and SWRe.

MOR and MOE were predicted by linear equations (Eqs. 1 and 3) and exponential equations (Eqs. 2 and 4), respectively.

$$MOR = 61D + 0.54851G + 0.14082L/t - 34.283 \tag{1}$$

$$MOR = (D)^{2.4892} \cdot (G)^{0.3165} \cdot (L/t)^{0.20578} \cdot e^{2.3656} \tag{2}$$

$$MOE = 6377.6D + 71.94G + 18.572L/t - 388 \tag{3}$$

$$MOE = (D)^{2.6809} \cdot (G)^{0.41046} \cdot (L/t)^{0.27956} \cdot (e)^{6.6005} \tag{4}$$

Where, MOE and MOR are modulus of elasticity and modulus of rupture, respectively; *L*, *W* and *t* are length, width and thickness of particles, respectively. *D* is board density (g·cm^{-3}) and *G* is resin content (%).

To investigate the interaction between slenderness ratio and resin content, two-dimensional diagrams were drawn by Maple 9 software. Both the linear and exponential functions indicated that slenderness ratio is more effective than resin content for estimating MOR and MOE. On the basis of linear function, as the slenderness ratio and resin content increased, MOE and MOR increased linearly (Figs. 2 and 4). But the exponential function showed that as resin content increased from 8 to 11%, particles with high slenderness ratio led yielded greater increases in MOE and MOR values than did particles with low slenderness ratio (Figs. 3 and 5).

At equal resin content, large particle size increased the mechanical strength of particleboard more than large specific surface (small particles). The exponential function described the relationship of slenderness ratio to resin content better than did the linear function. Average errors for MOR and MOE were obtained from Eq. 5. The exponential function predicted MOR and MOE with less error than did the linear function (Table 2). An exponential function was therefore found to be suitable for mod-

eling the mechanical properties of particleboard.

$$\% MAE = \frac{1}{n}\sum_{i=1}^{n} \left| \frac{z(x_i) - z(x_J)}{z(x_i)} \right| \times 100 \qquad (5)$$

where, MAE, $z(x_i)$, $z(x_J)$ and n are the average absolute error, experimental value, predicted value, and the number of treatment, respectively.

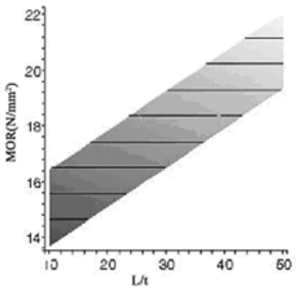

Fig. 2 2D diagram of MOR based on a linear function

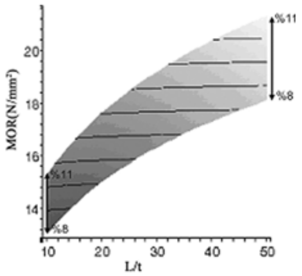

Fig. 3 2D diagram of MOR based on an exponential function

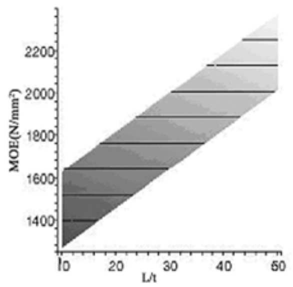

Fig. 4 2D diagram of MOE based on a linear function

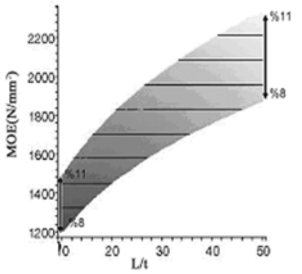

Fig.5. 2D diagram of MOE based on an exponential function

Table 2. Average error percent of mechanical properties

Mechanical properties	Average error percent	
	Exponential function	Linear function
MOR	14.82	18.13
MOE	10.13	16.9
IB	19.17	35.6
SWRe	13.34	16.71

We analyzed the relationship between slenderness ratio and resin content on IB strength. Both the linear (Eq. 6) and the exponential functions (Eq. 7) indicated that IB strength declined with increasing slenderness ratio (Figs. 6 and 7).

$$IB = 0.6924D + 0.034079G - 0.002285L/t - 0.31083 \qquad (6)$$

$$IB = (D)^{1.1843} \cdot (G)^{0.75245} \cdot (L/t)^{-0.12489} \cdot e^{-1.7228} \qquad (7)$$

Several studies showed the decline in IB strength with increasing particles size (Maloney 1977; Sun and Armia 1999; Miyamoto et al. 2002). Higher slenderness ratio offers a higher available surface area for resin coverage, but with increasing slenderness ratio IB strength decreased. However, according to the exponential function (Eq. 7), IB strength did not decline linearly: It showed an initial sharp decline as slenderness ratio increased from 12.87 to 21.52, after which its slope becomes almost constant (Fig. 7). In contrast, a linear function (Eq. 6) showed a linear decline in IB strength with increasing slenderness ratio and resin content (Fig. 6). Previous studies concluded that increasing slenderness ratios resulted in higher percentages of void areas in particleboard (Lin et al. 2004) and higher percent resin coverage on particle surfaces (Scott 2001; Lin et al. 2004). With increasing particle size, the percentage of void areas in particleboard did not vary according to a linear function (Lin et al. 2004). On the other hand, with increasing slenderness ratio, the void areas increased more than did resin coverage areas (Lin et al. 2004). The percenttage of void areas has a negative effect on IB strength, and also with increasing length and width, resin irregularly distributes on particle surfaces. Fins fill the voids and increase the IB strength (Nemli 2003; Sackey et al. 2008). Dai et al. (2008) showed that the relationship between inter-element contact and mat density is highly nonlinear and strongly affected by particle thickness. In addition, predicted values of IB strength based on an exponential function had smaller average error than did values based on a linear function (Table 2). Therefore, based on particle size and resin content, the exponential function predicted IB strength of particleboard better than a linear functional. Also it showed that particle size is is a stronger determinant than resin content of IB strength.

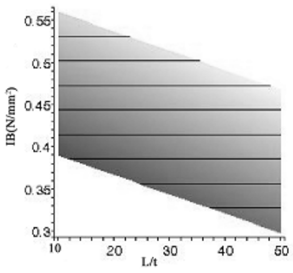

Fig. 6 2D diagram of IB based on a linear function

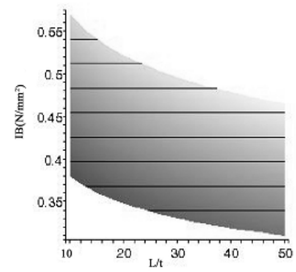

Fig. 7 2D diagram of IB based on an exponential function

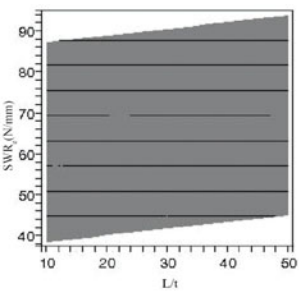

Fig. 8 2D diagram of SWRe based on a linear function

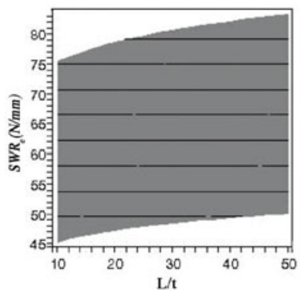

Fig. 9 2D diagram of SWRe based on an exponential function

The impact of the relationship between slenderness ratio and resin content on SWRe was analyzed based on linear (Eq.8) and

exponential functions (Eq. 9).

$$\mathrm{SWRe} = 0.16181\,L/t + 3.5155\,D + 9.748\,G - 33.681 \quad (8)$$

$$\mathrm{SWRe} = (D)^{0.53922\mathrm{S}} \cdot (G)^{0.44651} \cdot (L/t)^{0.0621} \cdot e^{3.1270} \quad (9)$$

Although IB strength predictions from an exponential function had smaller average error than those from a linear function (Table 2), neither showed increase in SWRe values as slenderness ratio increased (Figs. 8 and 9). Previous studies concluded that particles with large surface area had greater resin coverage and this led to greater mechanical strength (Maloney 1977; Sun and Armia 1999). But our results showed that SWRe did not increase with slenderness ratio when adhesive percent was constant. Sacky et al. (2008) demonstrated that the shorter and thicker particles yielded more overlap and this increased SWRe of particleboard. It seems that shape and size of particles were more effective than resin content as determinants of SWRe, and that improvement of the bonding strength of particleboard is best achieved by controlling particle size.

Conclusion

Determining the mechanical properties of wood composite is time-consuming, and requires expensive testing equipment. Therefore, a precise and simple tool to predict the physical and mechanical properties of wood composites would be valuable to the industry. There are many variables that influence the accuracy of models. Among these variables, the methods of modeling and the numbers and types of parameters used for modeling have the strongest influence. The difference between the surface area of large versus small particles, and the effect of this difference on percent resin coverage affects the predicted error percentage. Under a constant adhesive percent, MOR and MOE increased more at higher slenderness ratios, while SWRe of particleboard does not show this response. Lower values for IB strength were obtained at the highest slenderness ratios. We found the exponential function predicted mechanical strength of particleboard with smaller error than the linear function.

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